THz Instruments for Space Exploration

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***Abstract*—THz heterodyne spectrometers, capable of providing spectral resolution of >10^6 and detection sensitivity in the parts-per-billion range, provide a unique capability for space exploration. The exact operating frequency and technology for the instrument is driven largely by the science that is being investigated along with pragmatic concerns for mass and power requirements. These instruments are examples of highly complex systems that involve design, integration and testing of diverse technologies such as THz cryogenic detectors, optical elements, and microwave and submillimeter-wave components. This paper will review some of the advanced microwave and submillimeter-wave technologies that are being developed to create the next generation of THz instruments for space exploration.**

Keywords—THz technology, submillimeter-wave receivers, heterodyne receivers, THz instruments, space instruments

I. Introduction

Electromagnetic spectrometers covering the microwave, millimeter, and submillimeter wave regime provide a unique diagnostic tool for the physical world. Technologies and techniques such as radars and receivers are now ubiquitous and integrated in everyday life. These technologies are also used for space instruments. THz space instruments have been deployed with increasing regularity in the last three decades as THz techniques and tools have become more readily available. An intriguing part of the puzzle is the selection of the exact frequency of operation for any particular space instrument. While for earth based applications, frequency selection is somewhat arbitrary, even in some instance being determined by licensing agencies, the frequency coverage needed for space instruments is strictly driven by fundamental science needs. For example, the water molecule has a strong ground state rotational transition at 557 GHz. Thus, the Microwave Instrument on Rosetta Orbiter (MIRO), designed to measure water on comet 67P/Churyumov-Gerasimenko utilized Schottky diode mixers operating at this frequency [1] (water also has a number of other rotational lines, for example, 183 GHz, and so on with varying strengths). Similarly, other dipole molecules have unique frequency signatures, thus determining the exact frequency required for measurements.

The Microwave Limb Sounder (MLS) instrument, developed to measure ozone in the earth's atmosphere, had receiver channels at 118, 190, 240,640, and 2.5 THz [2]. A third example of a successful THz instrument is the Herschel Space Observatory (HSO), which had multiple instruments on-board and the heterodyne instrument consisted of six different bands that spanned 480 to 1908 GHz [3]. HIFI employed cryogens to cool the detectors for high sensitivity astrophysics research. The fact that the atmosphere around earth is extremely opaque in this frequency range requires use of space borne instruments.

THz instruments for space can be divided into two broad categories. The incoherent instruments provide exquisite sensitivity and a relatively large operational bandwidth. The detectors essentially "see" the full electromagnetic spectrum and filters are used to "define" the bandwidth of interest. In such instruments detector sensitivity is important and the detectors are often cooled to sub-mK temperatures to provide ultimate sensitivity. The major limitation with these instruments, specifically, for spectroscopy is the limited spectral resolution that can be achieved. To achieve ultimate sensitivity, it is also important to

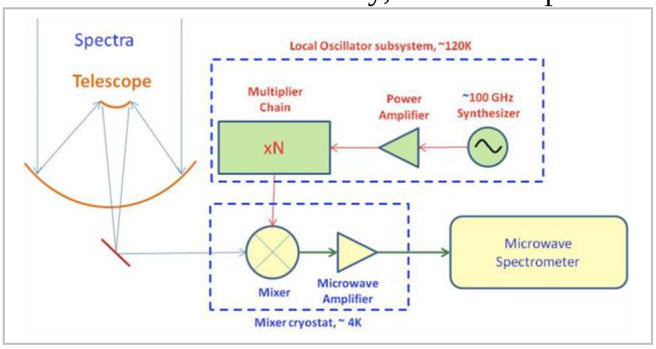

Fig. 1: Nominal heterodyne receiver for THz instruments. A number of critical subsystems involve microwave and submillimeter-wave technologies.

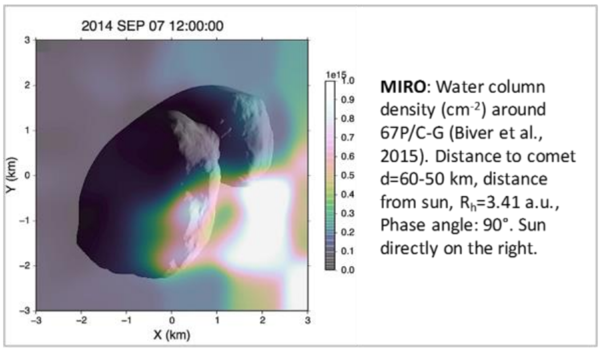

Fig. 2: Water vapor measurement on Comet P67 with a heterodyne instrument shows water column density.

cool the telescope in such instruments. A nominal heterodyne instrument, that requires 4K temperature for the mixers and 120K for the local oscillator (LO) subsystem is shown in Fig. 1. Nominally a dish is used to collect the incoming radiation. The three key subsystems of such an instrument are the mixers, the local oscillator, and the backend spectrometers. Obviously, there are other important subsystems such as instrument control unit, thermal management, structural and optical designs which are not covered in this paper. The mixers determine the ultimate sensitivity of the instrument and will be discussed later.

II. Motivation

THz instruments are used from understanding the chemistry behind ozone depletion to measuring water columns on comets. Fig. 2 shows the measurement made by MIRO on Comet P67 [4]. The Microwave Limb Sounder (MLS) was launched in 2004 and provided the first global measurement of ozone in the atmosphere, providing the impetus for reducing CNC gas emissions.

For earth, there is considerable focus on understanding climate and factors affecting change. One example of an important science measurement is measuring cloud dynamics. Both NASA as well as ESA has funded programs in the submm-wave to address this need [5]. Another intriguing unknown is the dynamics of winds in the upper atmosphere that are directly influenced by the sun and have a bearing on climate. Scientists have suggested to measure this by measuring the neutral oxygen line (feature at 2.06 THz).

For planetary science, ESA has funded the Submm-Wave Instrument (SWI) being built in Europe that would journey to Europa and measure water as well as methane (channels at 600 and 1200 GHz) [6]. To explore planetary atmospheres, submm-wave techniques have proven to be very effective and await opportunities to fly instruments for close-up measurements [7].

The HIFI instrument on Herschel was a major advancement both in terms of technology maturation as well as making measurements on major topics such as the dynamics of star formation. Currently, NASA is investigating the possibility of a large 9-meter dish instrument for far-Infrared astronomy which will include THz instruments if selected for funding [8].

A critical component for space instrumentation is the selection of the appropriate detector technology. This is primarily driven by the application at hand but also dependent on pragmatic concerns such as available mass and power resources. For astrophysics, where one is not back-ground limited, it is of utmost importance to have extremely sensitive detectors. This often requires cryogenic detectors to reduce thermal noise, but also necessitates the use of cryogens or cryo-coolers. On the other hand, an instrument designed to map a comet can afford to fly room temperature detectors if its going to rendezvous with the comet and be able to make observations from close distance.

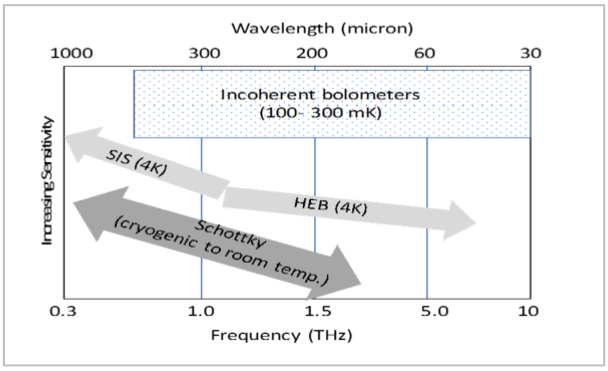

Fig. 3: Qualitative comparison between different detector technologies. For coherent detectors, a number of options exist and the choice is determined by sensitivity and programmatic needs.

III. THz Heterodyne Instruments

The heterodyne receiver is a commonly used block in radio sets. However, building a THz receiver is fraught with challenges. The heart of the heterodyne receiver is the detector element. While a number of devices can be utilized for this purpose, the selection of the appropriate technology is dependent on the required sensitivity and operational resources. The HEB and SIS devices both require cooling to 4K which requires significant more work in designing the instrument as well as operational resources.

An active field of research is developing solid-state tunable sources that can generate coherent radiation in the THz range to form the LO for the heterodyne receivers. A recent review is presented in [9]. Recent progress and expected results are shown in Fig. 4, showing that multi-pixel instruments in the THz range are now possible.

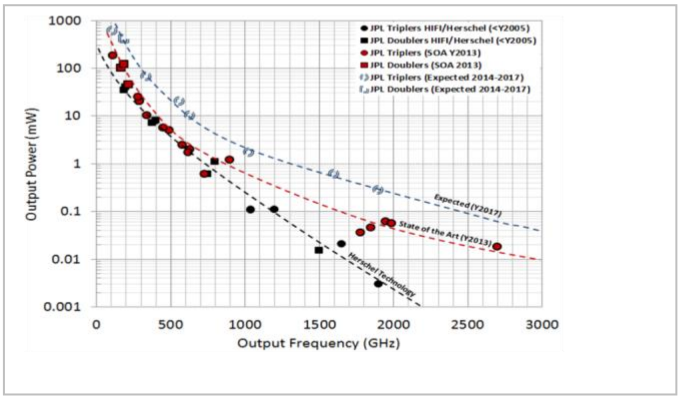

Fig. 4: Solid state local oscillator sources have made tremendous progress in the last few years. It is now possible to envision multi-pixel THz receivers for space missions.

IV. Recent Advances

A. *Infusion of CMOS Technology*

Tremendous strides have been made in increasing the frequency performance of silicon technologies. While the sensitivity and performance of silicon for submm-wave applications is making considerable advances, silicon technology will certainly be a part of future heterodyne instruments in at least three very important roles. The first and obvious one is the use of CMOS for command and control electronics. Traditionally, FPGA based electronics have been used but with maturation of flight qualified silicon technologies this will change based on mass and power arguments.

Secondly, and this is specific to heterodyne instruments, the backend spectrometers will be CMOS based. Considerable work is currently on-going to extend the bandwidth and performance of CMOS based back-ends, recent progress and expected performance are shown in Table I [10]. A third area where CMOS will make a difference is at the lower frequency voltage controlled oscillators. These are building blocks for LO circuits and CMOS VCOs have been demonstrated to over 500 GHz though not with sufficient output power as of yet. However, VCO's in the 100 GHz range are now being used that provide frequency agility with extremely low DC power, mass and volume [11].

Table I: CMOS System-on-Chip (SOC) backends will enable low power backends for future heterodyne instruments, they provide considerable advantage over traditional FPGA approaches.

Product / Feature	ROACH-II (UCB) (2013)	CMOS SOC UCLA/JPL (2015)	CMOS SOC UCLA/JPL (2016)	CMOS SOC UCLA/JPL (2017)	CMOS SOC UCLA/JPL (expected)
Bandwidth (GHz)	4	1	1.5	3	6
Channels	4096	512	2048	4096	8192
Power (W)	40	0.28	0.65	1	1.2
Size (cm^3)	50x40x10	10x8x2	10x8x2	10x8x2	10x8x2
Mass (Kg)	3.5	0.12	0.12	0.12	0.12
Tech.	Xilinx FPGA	65 nm CMOS	65 nm CMOS	65 nm CMOS	28 nm CMOS

B. *Multi-pixel THz receivers*

Generation of LO power remains a critical challenge in enabling array THz instruments of the future. Schottky diode multipliers driven by InP and GaN based power amplifiers, with power combining have been established as the baseline [12]. These sources utilize extremely low parasitic schottky diodes that are made on very thin substrates (membrane diodes). Currently, 16-pixel local oscillator sources at 1.9 THz have been demonstrated, enabling array based instruments for the future. Details of this subsystem have been presented [13].

C. *Nano-technology*

Future instruments, especially ones deployed to the outer planets will have to be compact and require very little power. Recent gains in nano-technology can be utilized to help with future heterodyne receivers. Nano-technology can provide a number of advantages and will continue to make inroads. A couple of concepts are already at the stage where they can be incorporated in future instruments. Work on high frequency MEMS based components has made considerable progress in the last few years [14]. Such components can provide clear advantages compared with traditional components such as flip-mirrors for calibration and beam steering. Another aspect of nano-technology important for THz instrumentation is on-going work on utilizing silicon based micro-lenses and waveguide cavities [15]-[18]. Silicon micro-machining allows one to make 3-D integrated waveguide circuits that can enable compact receivers. 3-D waveguides also allow for making structures such as OMTs which were not commonly used at higher frequencies due to higher loss. However, they can now be made in the THz range with acceptable losses.

V. SUMMARY

THz instruments provide clear advantages for space exploration. Recent advances in diverse technologies such as silicon micro-machining, CMOS system-on-chip, and array receivers will enable the next generation of space borne instruments that will provide drastic performance enhancement with acceptable loading on available resources.

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